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BEST PRACTICES FOR PROMOTING SCIENCE STUDENT TEACHERS' TECHNOLOGICAL PEDAGOGICAL CONTENT KNOWLEDGE (TPACK) IN LIFE SCIENCE

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ABSTRACT

This study identified the best practices for promoting 22 science student teachers' technological pedagogical content knowledge (TPACK) in life science at a teacher preparation institution in southern Thailand. This action research followed a four-stage process: (1) plan, (2) act, (3) observe, and (4) reflect. Each cycle involved reflecting on the outcomes to revise and improve teaching practice. The research was conducted over 64 hours through 11 lesson plans. Data were collected using post-lesson reports, semistructured interviews, lesson plans, students' diaries, and classroom observations. Qualitative data were analyzed through content analysis. Seven best practices were identified for promoting science student teachers' TPACK in life science: (1) surveying challenging life science topics, (2) building a clear understanding of TPACK, (3) demonstrating TPACK-based lessons, (4) designing and refining lesson plans with expert guidance, (5) engaging in microteaching and real-class teaching, (6) reflecting on teaching practices through self and peer evaluations, and (7) revising lesson plans based on feedback. These practices provide an effective framework for integrating technology, pedagogy, and content knowledge in life science.

Keywords: best practice; science student teacher; TPACK; life science

INTRODUCTION

Technological Pedagogical Content Knowledge (TPACK) has transformed science education by enabling the integration of technology with teaching methodologies and subject expertise. The Thailand Ministry of Education (2019) noted that TPACK is essential for transdisciplinary integration and practical application in the Bachelor's Degree in Education Program. This framework empowers science teachers to present complex scientific concepts in engaging and accessible ways, thereby fostering innovative teaching and meaningful student engagement (Demirdöğen et al., 2015; Nilsson & Vikström, 2015; Evi et al., 2017; Irwanto et al., 2022; Fakhriyah et al., 2022; Safriana et al., 2023). TPACK not only enhances classroom technology integration but also supports student teachers' professional growth by equipping them to meet the evolving demands of contemporary education.

Teachers often face challenges in mastering TPACK, especially with regard to effectively integrating technology into their teaching practices. A study of 217 teacher candidates found a generally high mastery of TPACK but also revealed that many struggled with practical integration due to insufficient training and resources (Kıylık & Kılıç, 2023). Similarly, a study involving 232 biology teachers revealed strong pedagogical knowledge (83.35%) but weaker technological knowledge (76.84%), highlighting a gap in TPACK proficiency (Nuruzzakiah et al., 2022). A survey of 369 mathematics teachers further emphasized the need for enhanced TPACK, particularly in effectively utilizing educational technology, and

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pointed to a widespread challenge in this area (Özen & Kurtuluş, 2023). These findings indicate the critical need for targeted professional development and resources to bridge the gap in TPACK proficiency, especially in effectively integrating technology into teaching practices.

Similarly, student teachers often struggle with TPACK owing to compartmentalized learning and limited opportunities for hands-on practice in blending content, pedagogy, and technology. A practical approach such as microteaching, as suggested by Pornsima (2019), can help student teachers build confidence and integrate these three domains effectively. Microteaching enables student teachers to practice their skills, receive feedback from peers and experts, and refine their approaches before beginning their professional internships. In the context of life science, developing TPACK goes beyond basic instruction—it requires student teachers to deeply understand the content and present it effectively by using technology in ways that align with the unique characteristics of life science (Pornsima, 2019). Therefore, a comprehensive approach that integrates both theoretical knowledge and practical application is necessary to bridge the gap in TPACK proficiency and ensure that future educators are well-prepared for the evolving demands of modern classrooms.

Pedagogical Content Knowledge (PCK), a key part of TPACK, can be challenging for student teachers in biological science to master as it requires subject knowledge as well as effective teaching practices and the ability to adapt information to meet diverse learner needs (Chapoo et al., 2018; Ramchand, 2022; Mapulanga et al., 2024). Many student teachers face difficulties in developing PCK in biology, as this field involves navigating complex topics like biogeochemical cycles, endocrine systems, cell division, and genetics (Chapoo et al., 2014 ; Gupta, 2019; Lawsin et al., 2022; Birzina, 2023). Studies indicate that low levels of pedagogical knowledge (PK) of biological science teachers make it challenging for them to integrate pedagogy with technology effectively (Yilmaz, 2016; Tanak, 2018). The complexity of biological content coupled with the need for tailored teaching strategies create a demanding learning environment (Çimer, 2012). Most teachers neither fully understand nor utilize TPACK in classrooms, often viewing technology as simply a supportive tool rather than an integral part of instruction (Jen et al., 2016; Padmavathi, 2017; Purwianingsih et al., 2022; González & Bravo, 2023; Bariroh & Surtikanti, 2024). Structural and resource-based challenges further complicate TPACK integration in science education. Many science teachers face difficulties in effectively presenting content and engaging students owing to factors like inadequate training in indigenous knowledge integration (Mkhwebane, 2024), ineffective teaching methodologies, and insufficient technological resources (Forbes et al., 2015; Otrel-Cass, 2015; Ruparanganda, 2019; Drew et al., 2023; Ramnarain et al., 2023; Relela & Mavuru, 2023; Siphukhanyo & Olawale, 2024). Additional obstacles include students' lack of prerequisite skills, faculty perceptions of content relevance, and limited access to digital tools, all of which hinder the seamless adoption of TPACK in classrooms (Forbes et al., 2015; Relela & Mavuru, 2023; Drew et al., 2023).

To overcome the abovementioned challenges in science teacher training, this study employs TPACK as a strategic framework to support the professional development of student teachers in life science. TPACK's integrated approach provides a pathway to enhance teaching efficacy, improve curriculum alignment, and address specific needs in life science teacher training. The central research question of this study is as follows: "What are the best practices for promoting the TPACK of science student teachers in life science?" This study aimed to identify the best practices for promoting the TPACK of 22 science student teachers in life science at a teacher preparation institution in southern Thailand. By focusing on classroom-based strategies, this study sought to empower student teachers in life science to effectively integrate content knowledge, pedagogical techniques, and technology in their teaching practices.

METHODS

Phase 1: Studying problems and challenges related to TPACK in life science based on student perception (4 weeks)

The researcher surveyed problems and challenges related to the pedagogical contents of life science among 3rd year student teachers through interviews about the same, a survey on TPACK, and a questionnaire about life science topics perceived to be difficult for learning management. Then, these findings were used for designing learning management activities for the Science Method Course in Phase 2.

Phase 2: Developing activities for the Science Method Course to promote science student teachers' TPACK in life science (12 weeks)

The researcher developed activities designed to promote science student teachers' TPACK in life science through the Science Method Course. This phase followed the iterative Plan, Act, Observe, and Reflect (PAOR) framework to ensure systematic development and continuous improvement of learning activities.

(1) Plan: The researcher planned the learning activity design and identified obvious work plans for learning management innovations (i.e., media and approaches). The researcher also planned the preparation of evidence for the pedagogical contents of life science (i.e., pedagogical management plan, lesson plans, topics, and activities). We considered the congruence with course descriptions and research highlights. The researcher planned to develop data collection instruments.

(2) Act: The researcher performed the planned activities to promote science student teachers' TPACK in life science.

(3) Observe: The researcher observed the learning management of student teachers' pedagogical content knowledge of life science and technology using post-lesson reports, semistructured interviews, lesson plans, students' diaries, and classroom observations to collect comprehensive and varied data.

(4) Reflect: The researcher used the results of the previous stage to analyze the problems and drawbacks of learning management that affected the development of TPACK in life science. The researcher refined and enhanced the learning management process in subsequent cycles based on insights and observations from the previous cycle.

The researcher sought the support of three science education experts to ensure that the activities were aligned with best practices for promoting TPACK. Data collection instruments were tested for their quality, along with content validity and suitability testing. The experts' criticism and suggestions were used for making further revisions and improvements.

Phase 3: Implemented activities for the Science Method Course to promote science student teachers' TPACK in life science (16 weeks, 4 hours per week, totaling 64 hours)

The researcher conducted learning management specifically designed to promote science student teachers' TPACK in life science. The implementation followed action research stages in the classroom through 11 lesson plans covering 64 hours of coursework. In the meantime, students received activity sheets or tasks related to contents/activities in that period. Activity plans were designed and tried out (i.e., action) during learning management. The researcher observed her own teaching with the learning management expert lecturers (PK), content expert lecturers, and technological expert lecturers (TK – Expert). They switched for observation and evaluation. Videos were also recorded during learning management. After teaching, the researcher reflected on the results and student performance in each cycle to identify areas for further improvement and development in the next cycle (i.e., reflect).

Cycle 1: Students surveyed difficult life science topics for learning management and searched for journals related to student misunderstanding, TPACK, and learning management technologies, especially for difficult or subjective topics as a representation of their mind. Then, they reflected on their performance and implemented the plans.

Cycle 2: The researcher transferred technological knowledge for learning management and discussed how to use applications for content and class management. Student teachers received feedback on their pedagogical styles and the conceptual framework of learning management demonstration through TPACK. Students considered, discussed, and criticized the components of each prototype plan. Then, they were instructed to practice activity design; write TPACK-based lesson plans; and present these plans to receive feedback from their classmates, researcher, and experts before their first microteaching.

Cycle 3: Students practiced microteaching in the simulated class and then performed a self-evaluation. The classmates, researcher, and experts also gave feedback to the students for further improvement in Cycle 4.

Cycle 4: Students performed pedagogical practice in class and then performed a self-evaluation. Then, classmates and the researcher gave feedback on further improvements and preparation for professional practice.

This work was approved for research implementation related to human research at Suratthani Rajabhat University, Thailand (Project no. SRU-EC2022/016).

Data were collected through 11 developed activity plans for 16 weeks, with lessons for 4 hours per week (i.e., for a total of 64 hours). After each period, the researcher, who was serving as the lecturer, wrote post-lesson reports covering different categories including student performance, affecting factors, problems, obstacles, and suggestions for future learning management.

Students wrote about different factors in their diary, including what they learned, opinions toward learning activities, problems, and suggestions. Additional interviews lasting around 20 minutes each were also conducted. Then, 4–5 students from each team practiced activity design and wrote TPACK-based lesson plans by applying innovative pedagogical approaches and integrating activities using technological tools for obvious relationships or changes. Then, these were combined with suitable pedagogical approaches for difficult life science topics. Each topic was covered over 1–2 periods (50 minutes per period). Then, students practiced their microteaching and pedagogical skills in school for 1–2 periods. Pedagogical plans, activity sheets, observation protocols, and the diary were included as the tools to evaluate the relationship between TPACK and practice. The quality of all research instruments was tested by three experts before real use.

All data obtained were used for content analysis. After the four cycles of learning management, the data were used for coding and finding coding relationships, interpreted to find common characteristics of objective data, and synthesized into issues to identify the best practices for promoting science student teachers' TPACK in life science. The accuracy of the analysis results was examined with critical friends.

In the reports, codes were used instead of participant names. For example, F19 and M18 referred to female student no. 19 and male student no. 18, respectively.

RESULTS AND DISCUSSION

The best practices for promoting science student teachers' TPACK in life science are as follows.

(1) Survey on difficult concepts of learning management for demonstration, practice writing plans, and pedagogical practice to promote perceived pedagogical examples, learn by direct experience through action, develop pedagogical skills, and increase the body of difficult content knowledge

In Cycle 1, the researcher surveyed five difficult life science topics, namely, chromosomes and genetic materials, biotechnology for animal productivity, genetic inheritance process, energy transfer, and diffusion and osmosis, that were congruent with the KPIs and core content of the Science Department (2017 edition) according to the Basic Education Core Curriculum 2008. The key causes of difficulties in learning management included complicated subjective contents, misconception in contents, and experimental/practical failures. One student noted the following:

"…There are a lot of contents that must be memorized, e.g., chromosomal crossover, matching, and occurrence of diseases. These all require memorization and understanding…" (F3)

As the contents of these topics were the obstacle for students' activity design, the activities in Cycle 2 were adjusted accordingly. Specifically, these difficult concepts were used as examples for pedagogical demonstration in Cycle 2 to enable students to consider the contents in more detail through suitable activities and pedagogical approaches. Next, students from all five teams (4–5 students/team) practiced the activity design and wrote TPACK-based lesson plans by applying innovative pedagogical approaches and integrating activities using technological tools for obvious relationships or changes. This was combined with suitable pedagogical approaches for one topic across 1–2 periods. Students from all five teams could design the TPACK-based lesson plans for difficult topics. The researcher also perceived their need for assistance, that is, pedagogical opportunity under simulated and real contexts. Accordingly, the activities were adjusted in Cycle 3 (microteaching in a simulated class) and Cycle 4 (pedagogical practice in science class). This process was necessary to help students develop their pedagogical expertise and implement their knowledge more efficiently. One student noted the following:

"Watching the demonstration, writing plans, microteaching, and teaching in real class brought me more confidence. I perceived how to teach, reviewed contents, and thought about how to transfer or present these contents for more participation and understanding from students." (F3's diary)

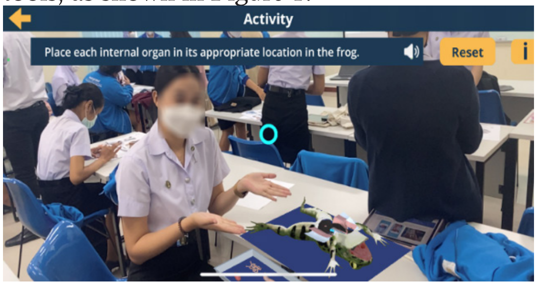
A survey on difficult concepts of learning management for demonstration, practice of writing plans, and pedagogical practice was conducted to promote perceived pedagogical examples, learn by direct experience through action, develop pedagogical skills, and increase the body of difficult content knowledge. Astolfi and Peterfalvi (1993) suggested that difficult scientific concepts are related to the representation of the teachers' mind in a science class. Therefore, putting these concepts into action (i.e., pedagogical practice) will enable students to see pedagogical examples, learn content analysis approaches, select pedagogical approaches, and select suitable technologies for transferring these contents into easily understandable forms as pedagogical prototype models that can be adapted in the future.

(2) Creating understanding of TPACK was a necessary foundation to develop student teachers' TPACK in life science

In Cycle 1, we discussed the concepts and theory of TPACK for life science, analyzed KPIs, searched for difficult life science topics from research, discussed pedagogical guidelines, clarified misconceptions, discussed the measurement of scientific concepts, discussed how misconceptions arise in difficult contents, and performed reflection. As a result, students could describe guidelines or the teaching of difficult topics. Most of them found that integrating technology made work attractive and interactive and enabled them to measure and evaluate their learning. However, the use of technology had some limitations for specific contents to describe natural phenomena. One student noted the following:

"I basically use instructional styles that motivate and attract students. I also promote the variety of knowledge. For example, I let students practice answering questions under limited time through Quizizz. I also tell them to submit assignments by Google Classroom or to watch knowledge-related videos through various channels." (Interview with F12)

Nonetheless, some natural phenomena cannot be seen with the naked eye; therefore, animations or 3D visuals must be used to support learning. During the interviews, we assumed that students had their own life science class and questioned how they would most efficiently conduct their learning management in that class. The results revealed that the learning approaches that students expected to use included scientific inquiry (41%), lectures (36%), cooperative learning (5%), game-based demonstrations (5%), demonstration videos (5%), scenarios (5%), and online lessons (5%). However, many students rated "lectures" as the second-most important approach for their class. This reflected that student teachers' knowledge of pedagogical approaches and strategies to support their learning was neither inclusive nor diverse. Therefore, the activities in Cycle 2 were adjusted. Specifically, the researcher managed students' experience to understand the basis of such knowledge. In Cycle 1, the students showed better development in some respects and what they needed for assistance, particularly the use of specific technology to focus on describing natural phenomena under subjective concepts, including specific pedagogical styles for contents to make pedagogical contents of life science clear, with guidelines on activities in Cycle 2. Therefore, the researcher educated student teachers about the pedagogical styles and technology with the use of applications as learning management tools, as shown in Figure 1.



(a) Frog dissection Activity Using Edmentum AR Biology

(b) Osmosis Activity Using Science Practicum Simulation

Figure 1. Applications as Learning Management Tools for Life Science Contents

The process revealed better development of student teachers, as the following student noted.

"I learned TPACK, in which technology was used to promote learning for a better quality learning process. It also made me realize the significance of technology and mistakes due to unsuitable technology. According to the analysis of case studies from teachers' videos, I thought we could make it better, even though it was already good, if teachers used suitable technology or added simulation media to reveal process/mechanisms inside. Moreover, I also learned and practiced how to use learning enhancement applications for more attraction and for extending more obvious concepts. I felt excited all the time during the study because I got to know various supporting technological media." (F14's diary)

As a result, students gained more obvious skills in using technology for learning management. They could also select suitable technologies for teaching specific life science topics.

Creating an understanding of TPACK was a necessary foundation to develop student teachers' TPACK in life science. Aktaş and Özmen (2020), Ali and Waer (2023), Bwalya et al. (2024), and Masnur et al. (2024) similarly reported that a TPACK-based course could improve and develop students' PCK, TK, TPK, and TPACK and equip them with better skills to select suitable technologies and pedagogical approaches for achieving learning outcomes.

(3) Demonstrating TPACK-based lessons as a good example and promoting learning experience

In Cycle 2, the researcher used demonstrations of TPACK-based lessons for life science as a good example and to promote learning experience. The demonstrations focused on helping students to perceive actions, with opportunities to practice their analytical thinking and discuss the components of TPACK in learning plans. Students could also analyze the strengths and weaknesses of these plans (i.e., prototypes). They observed regular learning management in this course, analyzed its strengths and weaknesses, and compared it with demonstrations of TPACK-based lessons. Then, they observed the pedagogical practice and took notes about observed skills with TPACK by using the theory and strategies they learned. They discussed integrated lecturers' and experts' pedagogical approaches or strategies with TPACK. The experts shared their knowledge, took part in demonstrations, analyzed and discussed the components of TPACK from lecturers' and experts' demonstrations, and described and recorded what they learned about the representation of their mind or strategies that could change content formats into easily understandable forms. The results in Cycle 2 revealed that students showed a better understanding of the use of TPACK to create guidelines on instructional activities and were able to identify what could represent their mind to change content formats into easily understandable forms, as noted by the following student.

"According to the demonstration video about plant response to stimuli, the first teacher used slides to represent contents, which indicated that plants' tips showed phototropism. Auxin formation on the side that was not exposed to light would promote more cell division. Therefore, the tips on that side underwent more cell division, and thus, they became longer and showed phototropism. I think this teacher could make me understand at a certain level but could have used the technology more to show clear images of the mechanism of auxin on that side. If I were her, I would add simulations for students to see clearer images of its mechanisms. When I watched the demonstration video of the second teacher, it was like 'YES', as it was exactly the same as what I was thinking. I understood today's lessons and was very happy." (F15's diary)

For demonstrating TPACK-based lessons as a good example and to promote learning experience, the results of this part agree with previous findings that microteaching is an efficient preparation for students (Korthagen, 2001; I'Anson et al., 2003; Bada & Akinbobola, 2022).

(4) Designing and developing TPACK-based lesson plans, with experts' criticism for revision of quality plans

In Cycle 2, students used their experience to design and develop their own TPACK-based lesson plans for difficult life science topics as a team (4–5 students/team). Students were informed in advance about what they would teach, for what purpose, and through which activities as well as how to use specific technologies. The researcher and students then reflected on the actions in this cycle together to plan for further improvement. As a result, students could design TPACK-based lesson plans, as noted by the following student:

"This week I had an opportunity to design and develop TPACK-based lesson plans for life science. It was the start of perfect development of these plans, and it enabled me to learn how to develop creative lesson plans with various activities in order to be congruent with the objectives. The plans were presented to classmates and lecturers for obtaining their suggestions. By doing so, I felt that my group must select technological tools that are more congruent with the contents and objectives. It must not be the general ones but the suitable ones." (F18's diary)

Despite their ability to design TPACK-based lesson plans for difficult life science topics, as revealed in the post-implementation criticism, some teams still selected quite unsuitable technologies and did not meet the objectives. For example, Team A (F1, M2, F8, F10, F18) designed a lesson plan on chromosomes and genetic materials. According to the core concept of this topic, the plan should not include only slides, as chromosomes and genetic materials cannot be seen with the naked eye. Students must be able to see the obvious relationships among chromosomes, DNA, and genes; the genotype being controlled by genes that are part of the DNA; and the DNA being part of the chromosomes in the nucleus. This team selected the Gizmos website to enable practice on genetic inheritance in birds. Although this technology was interesting, it was not congruent with the objective that required descriptions of the relationships among chromosomes, DNA, and genes from scientific models.

In Cycle 3, owing to the abovementioned limitations, the researcher told the other team members to share and suggest a lesson plan. The lecturers and experts reviewed the plan until it was perfectly revised. Students saw integrated activities using technological tools to reveal obvious relationships or changes and subjective materials turned into objective ones in combination with pedagogical approaches. The new technology selected was 3D chromosomal structures from the Sketchfab website, as listed in Table 1.

Table 1. Designing TPACK-based Lesson Plans Under the Topic "Chromosomes and Genetic Materials" for Grade 10

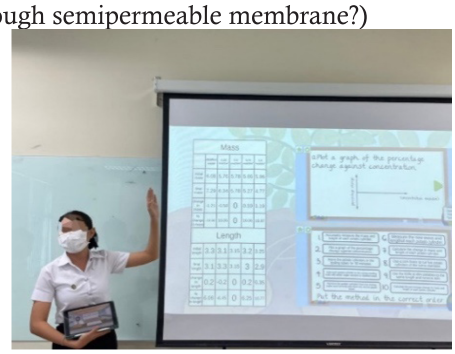
Team	**Team A: F1, M2, F8, F10, F18**
Topic	"Chromosomes and genetic materials" for Grade 10
Objectives	(1) To describe relationships among chromosomes, DNA, and genes from scientific models. (2) To develop a relationship model of chromosomes, DNA, and genes.
Activities	(1) Coded puzzles to describe genes as a unit that control creatures' genetic characteristics and to transfer characteristics. (2) 3D chromosomes to show relationships among chromosomes, DNA, and genes (3) Developing the structural and relationship model of chromosomes, DNA, and genes
Technology	3D chromosomal structures from Sketchfab website

For designing and developing TPACK-based lesson plans, with experts' criticism for making revisions to improve the quality of plans, the results revealed that the lesson planning process was difficult, complicated, and time-consuming for student teachers as it required the understanding of contents and pedagogical knowledge. Also, difficulties were faced in finding suitable activities for students of different levels. Further, a lack of experience in planning and activity management made students' lesson plans different from those of experienced teachers (Johnson, 2000; Tashevska, 2008; Nilsson, 2009). Nonetheless, pedagogical training programs could make students teachers realize the significance of efficient lesson planning (Azhar & Kayani, 2016; Saleh Moh'd et al., 2022). Lautenbach and Heyder (2019) suggested that students should practice outlining their lesson plans and activities during pedagogical practice. Then, they should take actions as planned, learn how to manage a suitable class, conduct group activities, facilitate the class, monitor students, and try to understand the roles of professional teachers. Students must practice these actions to prepare lesson plans efficiently.

(5) Microteaching in simulated class and teaching in real science class to promote pedagogical skills and confidence to apply knowledge into actions

In Cycle 3, after TPACK-based lesson plans were designed and developed, the next activity was microteaching to help students practice their pedagogical skills in a micro pattern, with 30 minutes per skill. Their practice was recorded in video and audio forms. Then, they were given feedback for further improvement. Microteaching helped students bridge a gap in developing their pedagogical knowledge combined with scientific contents while recognizing their shortcomings. Team B (F5, F11, F12, F22) conducted microteaching to describe the diffusion and osmosis process based on empirical evidences. They conducted experiments for hypothesis testing on this topic and exemplified diffusion and osmosis in daily life. Students used various activities such as diffusion testing (M&M Rainbow), diffusion experiments (wonder of walking water), osmosis experiments (how could water move through semipermeable membrane?), and technological integration to observe the molecular movement or diffusion of particles inside substances, referred from the PhET Interactive *Simulations website. They aimed to show particles' movement inside substances from a high-intensity spot to a low-intensity one by using kinetic energy. Equilibrium mechanisms, including diffusion states, in the diffusion of molecules or ions could be seen, and virtual experiments were performed through the* Science Practical Simulation application for an experimental study of osmosis in potatoes. The students demonstrated their measurement skills, drew conclusions from empirical evidences, and answered questions reflecting their understanding through the application, as shown in Figure 2.

(a) Osmosis experiment (How could water move through semipermeable membrane?)



(b) Virtual experiment on osmosis through Science Practical Simulation application

Figure 2. Microteaching about Diffusion and Osmosis

In Cycle 4, students taught in a real science class to promote their pedagogical skills and confidence to apply knowledge into actions by implementing their TPACK-based lesson plans. Their performance implied that they improved their teaching to be more perfect, as noted by the following student:

"I improved by exemplifying the situation to symbolize *particles' movement* under the topic of diffusion so that students could see the phenomenon more obviously. I used *PhET* Interactive *Simulations* to connect with the experiment on diffusion (M&M Rainbow) by setting a small blue circle to represent the water particle and a small red circle to represent the particle of a substance inside M&M. If M&M contained a higher intensity of particles than water, the particle inside M&M (red circle) would move to the low-intensity spot (blue circle) until the particles at both spots had equal intensity; this is called 'diffusion equilibrium'. This diffusion was independent and went to all directions." (Interview with F22)

For microteaching in a simulated class and teaching in a real science class to promote pedagogical skills and confidence to apply knowledge into actions, the results revealed that microteaching built students' confidence in TPACK (Race, 2001; Cinici et al., 2019) and partly helped them better understand the pedagogical process (Fernandez, 2010). Inexperienced teachers could develop their skills and compare the efficiency of microteaching with another style/pattern (Amobi & Irwin, 2012). Ali and Waer (2023) similarly revealed that such actions enabled students to learn how to use pedagogical technology. Students could develop this capability if they keep practicing continuously. Microteaching is an efficient strategy to promote pedagogical skills (Fernández, 2010; Haryani et al., 2021; O'Flaherty et al., 2023; Purwanti & Suhargo, 2024) and to minimize complication of related jobs to help students understand and learn pedagogical approaches (Reddy, 2019).

(6) Reflecting TPACK-based lesson plans to facilitate students' self-evaluation and to develop better pedagogical behavior

In Cycles 3 and 4, students reflected on the results of TPACK-based lesson plans to facilitate their critical thinking capabilities, self-awareness, self-perception, and self-evaluation for pedagogical improvement and gave suggestions for themselves or classmates to develop better pedagogical behaviors in class. In other words, students reflected on the results of their own teaching and classmates and evaluated TPACK in life science with lecturers and experts for realizing better teaching in the next cycle. Table 2 shows an example of reflection from Team C (F3, F4, F19, F20, F21) after a lesson on the genetic inheritance process for Grade 10.

Table 2. Example of Reflection from Team C on Genetic Inheritance Process

Topic	Genetic Inheritance Process (F3, F4, F19, F20, F21)
Reflection on TPACK-based lesson plan	- Knowledge was applied by exemplifying news of a pregnant actress whose baby's sex was not announced. Teachers asked students to calculate the probability of his/her sex. Other factors could be considered to create more challenging experiences, e.g., probability of a certain blood group. - Gene Screen application was used to teach students about basic knowledge of heredity and how to calculate the probability of the genotype and phenotype of the next generation. This application also includes genetic disorders, which could be considered as additional content for students.

Reflection on the results of TPACK-based lesson plans for life science in class enabled students to reflect on and examine their own and classmates' TPACK-based learning management for teaching better, as noted by the following student:

"The lesson plan and activities were implemented for real, which revealed drawbacks and what needed to be improved to attract students and to make it fun. According to the reflection from students, they enjoyed and paid attention to the lessons from the first week to the present. This revealed development of the created lesson plan. Previously, we neglected technological media. But when we practiced the provided program, students found the activities attractive and enjoyable, and it gave an opportunity to create models for easy understanding of contents." (F6's diary)

For reflecting the TPACK-based lesson plans to facilitate students' self-evaluation and to develop better pedagogical behavior, reflection on their own pedagogical practice might be rigid but useful (Loughran, 2002). It is a tool for better learning by thinking about perceived expectations and one's own feelings about experiences. It also builds understanding and enables learning from experiences for self-improvement and effective problem-solving (Johns, 2009). This is because the results of reflection will examine/verify student teachers' pedagogical practice and help improve their pedagogical content capabilities, particularly for science learning management, which requires an understanding of contents and congruent learning management with the nature of contents that focus on process and actions so that students will understand the acquisition of scientific knowledge (Jantrasee et al., 2018).

(7) Revising TPACK-based lessons for efficient learning management

In Cycles 3 and 4, students revised their TPACK-based lessons, namely, pre- and post-microteaching revisions and pre- and post-teaching revisions. Criticism from experts, lecturers, and classmates was used to make improvements to create the most perfect and efficient prototypes of lesson plans for use in the science class, as noted by the following student:

"Our group applied the revised lesson plan in a real class, which still contained some limitations, drawbacks, and areas of improvement, to provide a clear understanding while making things interesting for students. Therefore, we revised the lesson plan again for extending in our learning management next time for realizing a more perfect version."

Table 3 presents an example of post-microteaching revision of the lesson plan in terms of improved activities or technological tools.

Table 3. Example of Post-Microteaching Revision of Lesson Plan in Terms of Improved Activities or Technological Tools

Lesson plan	Energy Transfer, Grade 10 (F6, F9, F14, F15)
Pre-improvement phase of activities and applications	Presenting pyramid ideas from 1 randomized group, with the use of Gizmos to show a food chain model and describe balance of ecosystem. No time limit or reflection was set for this exciting activity.
Improved activities and applications	Each group presented their pyramid ideas to the class by using the Sheppard Software website instead of Gizmos to show their food chain model. Students must also answer about the types of creatures in sequence with an Online Stopwatch to create fun, excitement, and motivation for reflection by taking notes.

For achieving efficient learning management, students revised their TPACK-based lessons in two cycles, namely, pre- and post-microteaching revision and pre- and post-teaching revision. Criticism from experts, lecturers, and classmates was incorporated for improvement to create the most perfect prototypes of lesson plans. Lim et al. (2016) similarly revealed that lesson plans revised by students were more efficient than the initial ones.

CONCLUSION

This study identified seven best practices for promoting science student teachers' TPACK in life science and offered a comprehensive approach for integrating technology, pedagogy, and content knowledge effectively. First, surveying difficult life science topics provided a foundation for targeted pedagogical interventions. Second, creating a clear understanding of TPACK equipped student teachers with the knowledge to align technology with pedagogical strategies. Third, demonstrating TPACK-based lessons offered practical examples and opportunities to analyze effective teaching approaches. Fourth, designing and developing lesson plans under expert guidance enabled iterative improvement in teaching strategies. Fifth, engaging in microteaching and real-class teaching fostered confidence and refined pedagogical skills. Sixth, reflecting on teaching practices through self-evaluation and peer feedback encouraged continuous improvement. Lastly, revising lesson plans based on constructive criticism ensured the development of efficient, technology-integrated prototypes. Together, these practices provided a robust framework for equipping student teachers to meet the challenges of modern science education.

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